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An Approach for Estimating Soil Carbon Using the National Nutrient Loss Database

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ABSTRACT / Agricultural lands have the potential to contribute to greenhouse gas mitigation by sequestering organic carbon within the soil. Credible and consistent estimates will be necessary to design programs and policies to encourage management practices that increase carbon sequestration. Because a nationwide survey of soil carbon by the wide range of natural resources and management conditions of the United States is prohibitively expensive, a simulation modeling approach must be used. The National Nutrient Loss Database (NNLD) is a modeling and database system designed and built jointly by the USDA– Natural Resources Conservation Service (NRCS) and Texas A&M University to provide science-based inferences on environmental impacts from changes in agricultural management practices and programs at the regional and national level. Currently, the NNLD simulates 16 crops and covers $\sim 1.35 \times 10^8$ ha. For estimating soil carbon sequestration, the database will be populated with $\sim 1.5 \times 10^6$ field-level model runs using the EPIC (Environmental Policy Impact Calculator) model, which includes newly incorporated carbon equations consistent with those in the Century model. Each run will represent a unique situation defined by state, crop, climate, soil, irrigation type, conservation practice, tillage system, and nutrient management treatment (nutrient rate, application frequency, application timing, and manure category). Results are to be assigned to specific National Resource Inventory points (NRI) to simulate regional and national baselines. In this article we present the modeling approach and discuss the strengths and limitations.

Investigators report that carbon sequestered in agricultural soils may be one way to reduce concentrations of atmospheric greenhouse gases, which, in turn, may lessen global climate change (Lal and others 1999; Schlesinger and Andrews 1999). Furthermore, adoption of various crop management strategies or Best Management Practices (BMPs) can result in organic carbon buildup in the soil (Lal and others 1999). BMPs, however, are not universally applicable and typically are soil or regionally specific: A BMP under one set of conditions may not be a BMP under another set of conditions. Also, the effects are not singularly limited to carbon but can affect other system processes. These effects can be positive, negative, or some combination.

KEY WORDS: Nutrient Loss Database; Carbon sequestration; EPIC model; NRI

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The National Nutrient Loss Database (NNLD) is a modeling system and database that supports science-based, credible, and consistent inferences on environmental impacts from changes in agricultural management practices and programs at the national level. The NNLD was recently used in an USDA– NRCS (Natural Resources Conservation Service analysis to estimate changes in environmental impacts for a variety of conservation alternatives that were under consideration for the 2002 Farm Bill (USDA 2001a). Predecessors to the NNLD have been used in several national assessments, including congressional reports required under the Resource Conservation Act (USDA 1989; Putnam and others 1988; Putnam and Dyke 1987) and in identifying areas susceptible to pesticide contamination (Kellogg and others 1992, 1996). Currently, the NNLD is being used in a national study to assess the effects of implementing comprehensive nutrient management plans, and future plans include projects to track the environmental progress from implementing the 2002 Farm Bill. The NNLD provides the means to as the following:

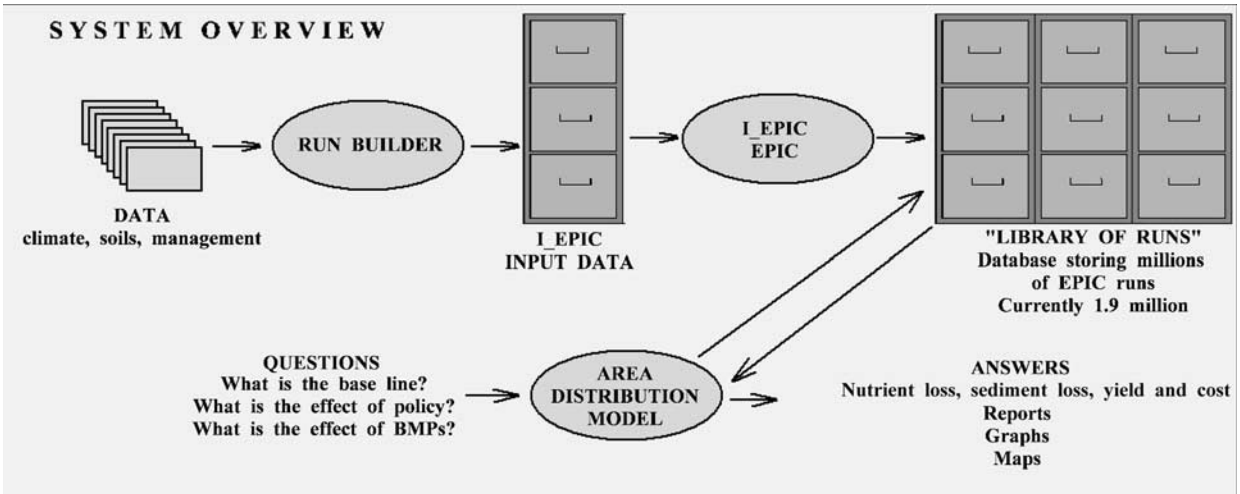

Figure 1. A simple schematic of the NNLD modeling system.

1 Compare the relative consequences of policy scenarios at the national level
2 Estimate national and regional non-point source (NPS) impacts from crop and pasture lands
3 Infer environmental impacts from changes in agricultural management practices

Two points are important: First, the NNLD is ready for making national assessments in the near term and, second, the NNLD is derived from accepted, time-tested tools. The following sections describe how the NNLD is set up for current studies. Some aspects would need to be optimized for evaluating carbon sequestration and those issues are discussed in the Conclusion.

Overview of Approach

The NNLD process works differently than in many other modeling systems (see Figure 1 for an overview schematic). In a relatively short time, we build thousands of model input datasets that cover numerous soil–climate–crop–management practice combinations. The I_EPIC program (Campbell 2000) was used to manage the input and output data and to automate the Environmental Policy Impact Calculator (EPIC) model runs. Once the runs are screened and validated, the input and output data are stored in the NNLD "Library of Runs" database. Area distribution and other simulation models are developed to estimate the effects of various policies and scenarios using data retrieved from the library. As input data, scientific knowledge, or models improve, we build new sets of input data and recreate the model runs to replace or supplement the NNLD.

The key source of input data for the NNLD is the US Department of Agriculture (USDA) National Resource Inventory (NRI) database (Nusser and Goebel 1997; USDA 2000b). The NRI is a comprehensive database that has been updated every 5 years with information such as soil type and soil- layer properties, landscape features, cropping history, and conservation practices for roughly one million "points" (each one representing an area of up to several thousand hectares) across the United States. The 250,0000 crop and pasture sample points available in the 1997 NRI serve as the underlying framework for the development of the NNLD.

Some management data, including irrigation status and erosion control practices, are in the NRI dataset, but other management data are lacking. Thus, management data are supplemented using several national datasets (Table 1). Because these data are not directly attributable to specific NRI sample points, the exact management scheme on any point is unknown. However, the probability that a management practice exists within a given area unit is known. Theoretically, our approach was to assign all management systems to all points within the respective areas units—in effect, replicating the sample point for each management. These replicate points are then assigned probability factors developed from the management datasets. In reality, this "all-combinations" approach is unworkable due to computational limitations. To get around this, the NRI points are grouped into clusters having similar climate regimes and soil characteristics. This results in ~ 35,000 unique resource units (URU), which are treated as representative points and modeled as homogenous fields (Atwood and others 2000).

Table 1. Management data sources for the NNLD modeling system

Management practice	Notes	Distribution method	Management area unit	Data source
Nutrient application rate and timing	Up to 50 different treatments per management area unit	Proportional weight	State–crop–dry/ irrigated	Cropping Practice Survey (USDA 2000a)
Manure application rates	Three farm classes: no manure, manure producer, manure Receiver	Proportional weight	State–climate zone–farm class–crop yield category	Census of Agriculture (USDA 2001b)
Irrigation method	Dryland, sprinkler, gravity	Area weight	Unique resource unit	National Resource Inventory (USDA 2000b)
Tillage system	No till, reduced till, conventional till	Proportional weight	County crop	Crop Residue Management Survey (CTIC 2001)
Conservation practice	Contours, strip, terraces	Area weight	Unique resource unit	National Resource Inventory

Note: A unique resource unit (URU) is a homogeneous modeling unit for an individual state, crop rotation, climate zone, soil, irrigation method, and conservation practice grouping.

On average, 35 model management systems were assigned to each URU and a model run was made for each using the EPIC agro-ecological model. EPIC is a daily time-step model that simulates plant growth, erosion, runoff, and leaching of water and nutrients (Sharpley and Williams 1990; Williams 1995). In its latest version, EPIC includes C and N dynamics consistent with those in the Century model (Izaurralde and others, 2001). Over 1.2×10^6 field-scale model runs were made, and these were stored and organized in a relational database system—the "library of runs." The library provides for two distinct sorts of investigation: analysis of the unweighted model runs and analysis of the weighted runs.

The unweighted model runs directly relate the input conditions to the output results and aid in examining field-level relationships between management practices and environmental impacts across regions, climates, and soils. This type of analysis was useful in judging the reliability of the output with respect to well-known processes. For instance, we checked that soil erosion decreased as tillage intensity decreased while other parameters were held constant. Also, these results were useful in gaining a better understanding of complex physical processes including interactions between components and the behavior of the whole system. Additional uses of these data could include the development of screening tools—for example, classification indices for carbon sequestration potential and testing of management strategies to determine the circumstances under which practices are most effective.

The second type of analysis weights each model run to produce a real-world view. First, an area distribution model was developed to link the NNLD runs to the NRI points. Then, the distribution model assigned the probability factors derived for the rates and timings of fertilizer applications, rates and properties of manure applications, and tillage methods. Finally, an area weight derived from the NRI sampling was applied. Those results were aggregated to various levels for developing baselines and should prove useful in producing per-acre-type coefficients to use in watershed and economic models for policy analysis.

Soil Clustering

There are about 30,000 different soils distributed across the 250,000 NRI points. In national assessments, a common data reduction technique is to group the soils and then select a representative from each group. In past studies, soil groupings have been typically based on proximity of the soils to each other; the soil with the largest acreage within a group was then selected to be the representative soil. Because many environmental effects are greatly influenced by the soils, a selection method based on soil properties was developed for the NNLD (Sanabria and Goss 1997). First, those soil properties most affecting runoff, erosion, fertility, and phosphorus adsorption were established (Table 2) and a soil attribute database was built. A factor analysis reduced those properties into several factors and the soils were grouped into clusters having similar factors.

Table 2. Soil attributes used in clustering procedure

1. Hydrologic group
2. Albedo (dry)
3. K factor
4. Horizon 1% silt
5. Horizon 1% clay
6. Horizon 1 bulk density (dry)
7. Horizon 1 organic carbon
8. Horizon 1 CEC
9. Horizon 1 pH
10. Number of horizons
11. Soil depth
12. Total available water
13. pH (minimum)
14. Field capacity (sum of all layers)
15. Organic carbon (sum of all layers)
16. $CaCO_3$ (sum of all layers)
17. CEC (sum of all layers)
18. Bulk density, dry (minimum)
19. Bulk density, moist (minimum)
20. Rock % (maximum)
21. Salinity (minimum value for the range in soil salinity of the soil layer or horizon measured as electrical conductivity of the soil in a saturated paste; Values expressed in mmho/cm)
22. Water table depth, low (Min value for the range in depth to the seasonally high water table during the months specified)
23. Water table depth, high (max value for the range in depth to the seasonally high water table during the months specified)
24. Water table kind [type of water table: apparent (APPAR); artesian (ARTES); perched (PERCH)]
25. Water table begins (month in which seasonal water table occurs at the depth specified in a normal year)
26. Water table ends (month in which seasonal water table subsides below the depth specified in a normal year)
27. Drainage class (code identifying the natural drainage condition of the soil and refers to the frequency and duration of periods when the soil is free of saturation. well drained (W); excessive (E); moderately well (MW); poorly (P); somewhat excessively (SE); somewhat poorly (SP)

Finally, the soil closest to the multivariate center of each group was selected as representative. This technique resulted in 2688 representative soils, which were then assigned to the appropriate NRI points. Figure 2 shows the number of soil clusters within each of the US Geological Survey (USGS) eight-digit Hydrologic Catalog Unit (HUC) watersheds included in the study (see Seaber and others (1987) for a description of the eight-digit HUC watersheds).

Climate Zones

Two different techniques were used to delineate the climate zones (Figure 3) in which the NRI points were situated. Areas east of the Rocky Mountains were delineated using a statistical clustering method and those in the west were delineated using a GIS approach.

A two-step process was used to determine the climate zones east of the Rock Mountains. First, subareas within the eight-digit HUC watersheds were assigned to the nearest weather station using a Thiessen polygon network. The station covering the greatest area within an eight-digit HUC watershed was then selected to represent the HUC.

Historic climatic data most affecting crop growth, erosion, runoff, and leaching were extracted from the EPIC-supplied weather data for these stations. The monthly data were organized into four periods per year: (1) December–February, (2) March–May, (3) June–August, and (4) September–November. To lessen the impact of outliers, the values were standardized to a mean of zero and standard deviation of one. Next, a factor analysis using a varimax rotation was performed. This procedure reduced the 51 variables to 6 climatic factors that captured ~70% of the variability in the original data. The weather stations were then statistically grouped into 35 clusters. One climatic station near the centroid of each climate cluster was chosen to represent all climatic stations in the cluster. See the work of Sanabria and Goss (1997) for further details of the clustering methods.

The western states were excluded from the statistical clustering because of extremely large climatic variations within small spatial extents, usually due to orographic effects. Thus, we derived the western clusters using a GIS-based approach. Using the data layers shown in Table 3, a GIS database was built. Using those data, GIS analytical tools, and expert judgment, weather stations were assigned to one or more HUCs. Only crop or pasture areas within each HUC were considered in making the assignments. This technique resulted in 31 climate zones, bringing to 66 the number of climate zones needed to represent the study areas.

Unique Resource Units

With each NRI point assigned to a soil and climate cluster, the next step was to group the NRI survey points according to the clusters, land use, presence and type of irrigation, and type of conservation practice system used. In the grouping process, the statistical average weights associated with the points were also accumulated so that for each resulting Unique Resource Modeling Unit (URU), the acreage weighted average slope, slope length, and Universal Soil Loss Equation (USLE) *P*-factor could be calculated.

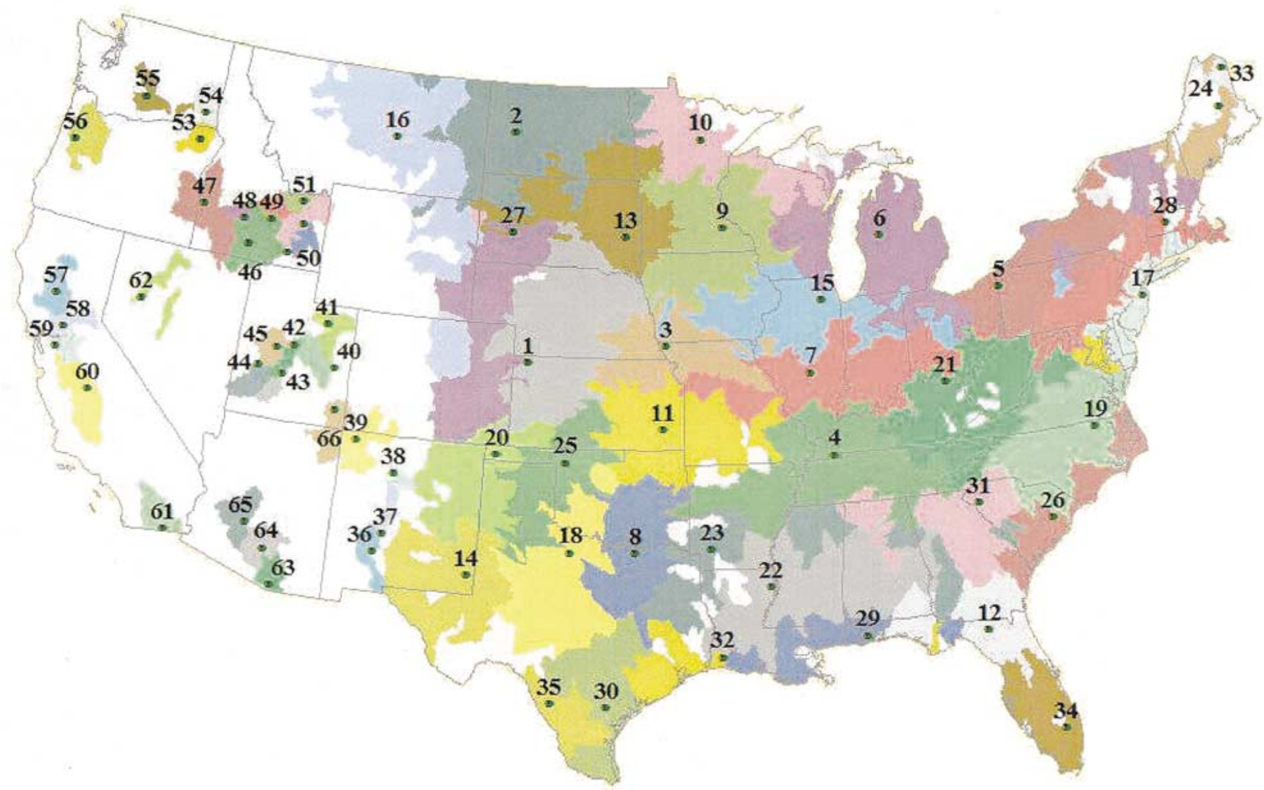

Figure 2. The number of representative soils modeled in each eight-digit Hydrologic Catalog Unit (HUC) watersheds.

The definition of unique resource units to model was primarily based on land uses recorded in the NRI. However, the NRI does not differentiate between grain and silage for corn, for different wheat types, and included several categories of hay and pasture that do not match well with Census of Agriculture definitions. For these cases, Census of Agriculture data available from the USDA (2001b), were used at the county level to divide each NRI corn point into grain and silage, each wheat point into winter and spring wheat, and each pastureland point into permanent pasture and cropland used as pasture. This procedure resulted in duplicate, relabeled points, having the same attributes as the original point, except for the acreage expansion factor that was divided according to the shares.

The NRI also indicated the type, if any, of irrigation system in place (dryland, sprinkler, and furrow/flood) and conservation practices that were used at each sample point.

Supplemental Management Data

The 1990–95 Cropping Practices Survey (CPS) was used to derive estimates of nutrient management for nitrogen and phosphorus fertilizer by state (USDA 2000a). For a given sample, the data can be quite extensive, including date of application of nutrient material, type of material, application method, and quantity applied. Because nearly every farmer does things a bit different from all others, it was necessary to define categories and to group the survey samples. The categorical grouping was by three classifications:

1. Dry or irrigated
2. Relative levels of N and P use (high, medium, and low)
3. Season and frequency of application (fall and spring and before, at, and after planting)

Manure is treated as a fertilizer material in the simulation model. Because the nutrient content of the manure varies according to livestock type, feed rations, and management practices, each specific manure defined in the analysis must be treated as a separate fertilizer material in the modeling system. The determination of the nutrient content of the manure for each climate portion of a state originated at the individual farm level, depending on the type of livestock, farm class, and the management practices used (Kellogg and others 2000). Individual farm results were

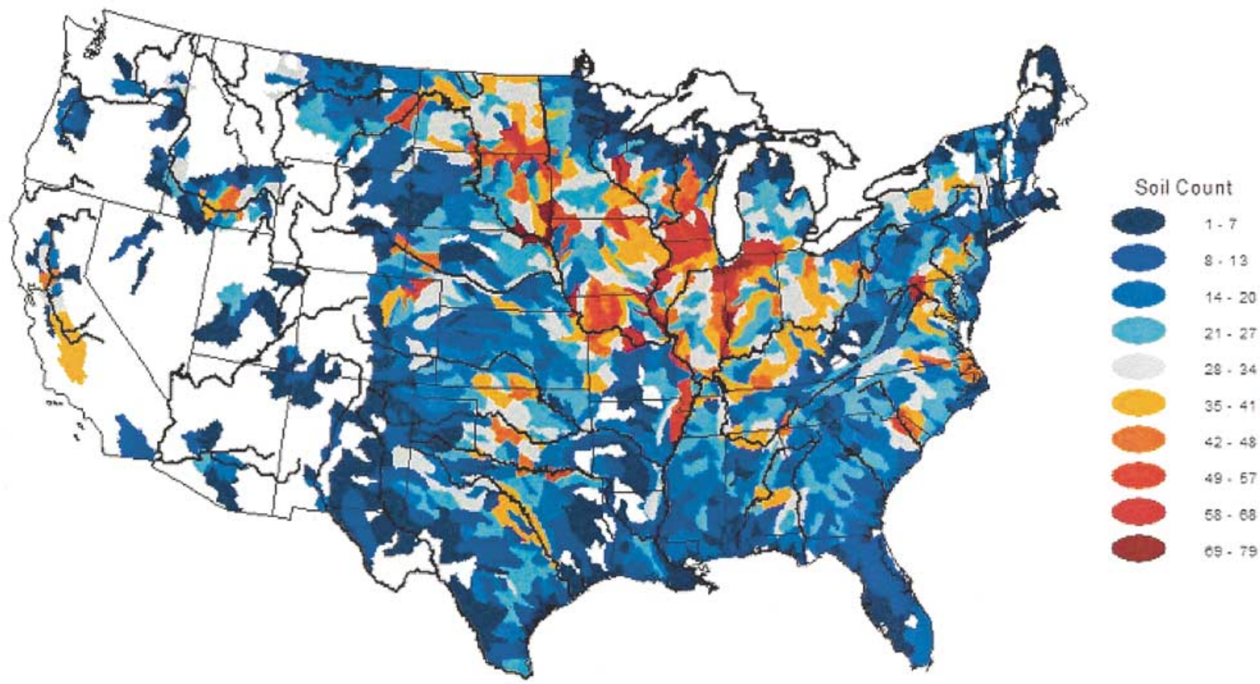

Figure 3. Climate zones and weather station locations. The zones east of the Rocky Mountains were made using a multivariate clustering technique. In the west, a GIS approach was used to derive the climate zones and weather stations. This resulted in smaller areas for the western zones, which were necessary because of extreme climatic changes within small spatial extents.

Table 3. GIS data layers used in selecting weather stations in the western United States

1. HUC boundaries
2. 1:250,000 Digital elevation models (DEM)
3. Land use and land cover (older USGS LULC and newer NLCD)
4. USGS/NOAA climatic zones
5. PRISMS climatic data (rainfall, temperatures)w
6. RUSLE rainfall brosivity zones
7. Major land resource areas
8. EPA eco-regions
9. Weather station locations

then aggregated to climate zone state part level for the two manure farm classes (producers and receivers). Fertilizer attributes specified for the manure include the proportions as follows:

1 Mineral N
2 Mineral P
3 Organic N form
4 Organic P form
5 Mineral N in ammonia forms (NH_4)

Because the available practice and NRI data were inadequate for determining tillage type and because the tillage type is expected to change over time at many of the points, we modeled three tillage types separately for each unique resource unit: conventional, reduced, and no till. Generic tillage schedules having soil preparation, planting, cultivating, and harvesting operations were developed for conventional, reduced, and no-till systems. Operation dates and crop maturity lengths were adjusted to reflect differences in each climate zone. The complete budget includes operations for fertilizer applications and irrigation scheduling. Tables 4 and 5 illustrate simple and complex budget examples.

EPIC Model

The NNLD uses the EPIC model to simulate the effects of implementing different management practices. EPIC is a widely used and tested agro-ecological model used in evaluating the environmental effects from changing cropping systems and management practices (Williams 1995). The model operates on a daily time step to simulate hydrologic, weather, soil, nutrient, crop practices and management, and pesticide effects. EPIC limits the simulation to a single field and does not extrapolate results beyond the edge of the field or deeper than the bottom of the root zone.

Under development since the early 1980s, the EPIC model has components to incorporate or estimate a

Table 4. A simple field operation schedule for no-till winter wheat on a nonmanure farm

Month	Day	Op code	Param 1	Param 2	Param 3	Param 4	Param 5	Param 6	HUSC	Description
10	10	82	0	1511	0	0	412.2	0	0.84	No-till drill plant; plant heat units to maturity: 1511; plant population:412 plants/m
11	9	71	64	127.8	0	0	0	0	0.26	Chemical fertilizer; type: 64; rate: 127.8 kg/ha
5	4	51	0	0	0	0	0	0	1.15	Harvest crop
5	5	41	0	0	0	0	0	0	1.15	Kill crop (dummy operation for model)

Note: Op code specifies the field operation, param 1–6 are model input variables, and HUSC is the heat unit scheduling code that sets the timing of the operation.

number of processes, including weather, water movement by surface runoff, return flow, percolation, ET, lateral subsurface flow, and snow melt, soil temperature, water and wind erosion, N and P losses in runoff, leaching, and volitization, organic N and P transport by sediment, nutrient transformations including mineralization, immobilization and uptake, denitrification, and fixation, pesticide fate and transport, crop growth and yield for over 80 crops, operation and management practices including crop rotations, tillage, drainage, irrigation, fertilization, furrow diking, and liming, economic accounting, and waste management features including feed yards, and dairies with or without lagoons.

EPIC version 1015 incorporates carbon cycle routines that are conceptually similar to those in the Century model (Izaurralde and others 2001). In this EPIC version, the new C routines are coupled to the hydrology, erosion, soil temperature, and tillage components—traditional strengths of the EPIC model. Two links are particularly noteworthy. One is the C transformation rate controls exerted by the soil temperature and soil water equations. The second uses the EPIC leaching equations to move C down through the soil profile. Furthermore, the authors report equations to capture the effects of soil texture on the stabilization of soil organic matter incorporated into the model.

National Nutrient Loss Database—Library of Runs

Over one million model runs, each for a 30-year period, compose the NNLD. Every run in the NNLD dataset consists of over 30 estimated output variables and is identified by a unique combination of 13 categorization variables (Table 6). Furthermore, several categorization variables are coupled to attribute databases. For instance, each of the 2688 soils is associated with over 50 attributes, including surface texture, hydrologic soil group, water table depth, and detailed layer data. These attributes can be joined to the output variables and the result is a rich, perhaps unmatched, collection of agri-environmental data. The ability to support the analyses of multiple environmental effects derived from numerous management practices implemented over a range of crops, soils, and climates is a key aspect of the NNLD.

Modeling Carbon Sequestration Options Using the NNLD

Agricultural soils function as either an atmospheric carbon source or sink. Lal and others (1999) state that the SOC content is determined by the balance between processes governing carbon sequestration and carbon emission. They further report that sequestration is enhanced by processes including humification, aggregation, calcification, and deep sequestration, whereas emissions are accelerated by erosion, leaching, methanogenesis, volatilization, and mineralization. The mechanisms are complex, interdependent and, in some cases, not well understood. The complexity of the relationships and interactions among the environment, cropping practices and nutrient cycles present many challenges in developing management strategies to enhance carbon sequestration.

No single mitigation strategy will work in every situation. Generally, best management practices are regionally and soil specific and different strategies will be needed to correct different mechanisms. In the NNLD, mitigation strategies can be applied at the field level by modifying the model run input parameters or at the national level by modifying the management or area weights. Best management practices

Table 5. A complex field operation schedule for conventional-tilled, sprinkler-irrigated corn on a manure-producing farm

No.	Month	Day	Op code	Param 1	Param 2	Param 3	Param 4	Param 5	Param 6	HUSC	Description
1.	1	1	9	0	0	0	−999	0	0	0.01	Turns auto-irrigate function on
2.	2	1	74	127	29.58	0	0	0	0	0	Surface applied manure ; type: 127; Rate: 29.58 kg/ha
3.	2	1	74	354	10.92	0	0	0	0	0	Surface applied manure; Type: 354; Rate: 10.92 kg/ha
4.	5	1	29	0	0	0	0	0	0	0.07	Tandem disk
5.	5	2	74	127	100.6	0	0	0	0	0.08	Surface applied manure; type: 127; Rate: 100.6 kg/ha
6.	5	2	74	354	37.13	0	0	0	0	0.08	Surface applied manure; type: 354; Rate: 37.1 kg/ha
7.	5	8	29	0	0	0	0	0	0	0.1	Tandem disk
8.	5	14	20	0	0	0	0	0	0	0.12	Field cultivate
9.	5	15	72	0	75	0	0	0	0	0.12	Irrigate 75 mm 1 week prior to plant
10.	5	21	71	64	220.9	0	0	0	0	0.15	Chemical fertilizer; type: 64; rate: 220.9 kg/ha
11.	5	21	71	65	81.55	0	0	0	0	0.15	Chemical fertilizer; type: 65; rate: 81.6 kg/ha
12.	5	22	2	0	1084	0	0.85	6.22	0	0.15	Row plant; PHU to maturity: 1084; water stress factor: 0.85; plant population: 6.22 plants/m^2
13.	6	12	19	0	0	0	0	0	0	0.15	Row cultivate
14.	6	26	19	0	0	0	0	0	0	0.28	Row cultivate
15.	8	7	9	0	0	0	−999	0	0	1	Turns auto-irrigate function off when crop reaches maturity
16.	9	22	51	0	0	0	0	0	0	1.15	Harvest crop
17.	9	23	41	0	0	0	0	0	0	1.15	Kill crop (dummy operation for model)
18.	10	7	74	127	67.05	0	0	0	0	1.23	Surface applied manure; type: 127; rate: 67.1 kg/ha
19.	10	7	74	354	24.75	0	0	0	0	1.23	Surface applied manure; type: 354; rate: 24.8 kg/ha
20.	10	13	30	0	0	0	0	0	0	1.25	Pt-Chisel
21.	11	29	29	0	0	0	0	0	0	1.25	Tandem disk

Note: Op code specifies the field operation, param 1–6 are model input variables, and HUSC is the heat unit scheduling code that sets the timing of the operation.

to enhance carbon sequestration and mitigate greenhouse gas emissions that could be modeled using the NNLD fall into four areas and the general practices are as follows:

1. Implementing soil erosion control plans
   A. Apply contours, terraces, strip-cropping
   B. Use conservation tillage
   C. Use cover factor as a guide to adjust tillage operations
2. Improving cropping systems management:
   A. Optimize operation timing
   B. Use crop rotations
   C. Use cover crops
   D. Optimize irrigation scheduling
   E. Implement soil drainage

Table 6. Classification variables and model outputs available in current NNLD dataset

ID	Name	Description	Unit
1	ID	Run ID number	Incremental
2	State FIPS	State FIPS	Category
3	Crop	Crop	Category
4	Man Cat	Manure application category	Category
5	Clim Clus	Climate cluster	Category
6	Soil Clus	Soil cluster	Category
7	Irr	Irrigation type	Category
8	Tillage	Tillage type	Category
9	App Cat	Application category	Category
10	N Rate Cat	Nutrient rate category	Category
11	App Time	Application timing category	Category
12	C Pract	Conservation practice	Category
13	P Fact	Practice factor	Ordinal
14	Slope	Slope	m/m
15	S Lngth	Slope length	m
16	Yield	Crop yield (dry weight)	tons/ha
17	Precip	Rainfall	mm
18	Irr Vol	Irrigation	mm
19	ET	Evapotranspiration	mm
20	Runoff	Runoff	mm
21	Perc	Percolation	mm
22	Sub Flow	Subsurface flow	mm
23	Drain Flow	Drain tile flow	mm
24	USLE	Water erosion (USLE)	tons/ha
25	RUSLE	Water erosion (RUSLE)	tons/ha
26	MUSLE	Water erosion (MUSLE)	tons/ha
27	Wind	Wind erosion	tons/ha
28	Ox C	Oxidized carbon	tons/ha
29	SOC	Soil organic carbon	tons/ha
30	NO3 RO	NO_3 loss in runoff	kg/ha
31	NO3 Leach	NO_3 leached	kg/ha
32	NO3 Sub FL	NO_3 loss in subsurface flow	kg/ha
33	N Sed	N loss with sediment	kg/ha
34	NO3 Drain	NO_3 loss in drain flow	kg/ha
35	N Vol	N volatized	kg/ha
36	T N Loss	Sum of all N loss (30–35)	kg/ha
37	PRO	Labile P lost in runoff	kg/ha
38	P Leach	Labile P lost in leachate	kg/ha
39	P Sed	P loss with sediment	kg/ha
40	T P Loss	Sum of all P loss (37–39)	kg/ha
41	P Min	P mineralized	kg/ha
42	STP	Soil test P (labile P in top two layers)	mg/kg
43	FPO	Fertilizer organic P	kg/ha
44	FPI	Fertilizer labile P	kg/ha
45	Tot FP	Total phosphorus fertilizer applied	kg/ha
46	FNO	Fertilizer organic N	kg/ha
47	FNO3	Fertilizer nitrate	kg/ha
48	FNH3	Fertilizer ammonia	kg/ha
49	Tot FN	Total nitrogen fertilizer applied	kg/ha

3. Improving fertilizer management
   A. Optimize rates, methods, and timing of applications
   B. Apply manure
   C. Employ soil phosphorus testing
   D. Apply nitrification inhibitors
4. Optimizing land use
   A. Shift marginal cropland to grass/Pasture
   B. Restrict use of sensitive land
   C. Restrict use of sensitive soils

The rate of change in soil organic carbon is both slow and irregular, which causes difficulties in documenting the effectiveness of management. In many cases, practices implemented to enhance carbon sequestration will affect other field-level processes. Usually these are beneficial, for example, lessening soil erosion, but there can be detrimental co-effects. Thus, it is important to estimate changes over multiple years and capture all the important environmental effects.

Conclusion

One limitation of the system is that the results are not time specific because results are derived from probabilistically generated weather. Using generated weather is a design feature of the NNLD system that allows estimates of future effects even though the actual weather of any given year is unknown. An added source of inaccuracies may stem from poor or missing input data. To compensate, 10 years are simulated prior to the start of the simulation of interest and the previous years of cultivation parameter is set. Furthermore, outputs from the system are edge-of-field results, which do not provide a complete picture of the environmental impacts, particularly when aggregating up to larger regions.

We are more confident in the accuracy when examining the relative responses to changes in management. One reason is the reliability of the EPIC model, which has been widely tested and verified for over 20 years. It is a proven and highly refined model. Another reason for confidence is that the outputs from the NNLD satisfactorily replicate the known effects from different management practices. Even when examining the outliers, we typically found solid, theoretical explanations for extreme values. Finally, although there are few national datasets available for evaluating the NNLD results, comparisons to yearly crop yield data from the National Agricultural Statistics Service and to soil erosion estimates for 1992 and 1997 from the NRI showed similar responses, with a few exceptions (Potter and others 2001).

There are several other strengths worth noting. The NNLD incorporates many soils to represent the variability of the cropland soil resources, and the selection of representatives is based on the physical properties that most influence environmental impacts. In addition, the NNLD was developed to take advantage of the sampling structure of the NRI, which allows for both spatial and temporal analysis. Furthermore, the NNLD captures many important environmental effects—not just those related to soil carbon. This will aid land managers and policymakers to more fully ascribe the benefits resulting from conservation plans and programs. Finally, the NNLD employs a relational database structure that is both functional for analyzing model outputs and is readily adaptable for expansion or revision using updated models and data.

To reliably estimate soil organic carbon, several enhancements to the NNLD need to be completed. First, EPIC version 1015 and the associated parameters should be incorporated into the NNLD. Although the required software changes to the NNLD system are complete, values for several of the new parameters still need to be determined. Second, techniques to represent the mitigation options in the modeling system need to be devised. This means developing clear, systematic rules to modify the model inputs or weights and then translating those rules into program code. Experience shows that this will be an iterative process. Finally, collaboration with others is essential in producing reliable national estimates for policymakers or for developing tools that are useful to land managers.

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